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A computer program, WAter Forces Analysis Capability (WAFAC), was developed to analyze forces acting on bodies in water. The WAFAC model computes buoyancy, wave-excitation, added-mass, and drag forces acting on a system of linked bodies in water. The bodies are assumed to be rigid ellipsoids. Sea states can be approximated by the superposition of up to ten regular waves or by a single regular wave of amplitude equal to the "significant wave height" and frequency based on the Pierson-Moskovitz spectrum for fully developed ocean waves. The WAFAC model is structured to compute components of force and moment due to buoyancy, wave-excitation, added-mass, and drag using separate modules. During development, each module was tested to assess the accuracy of the results predicted. The resultant water force and moment acting on each ellipsoid in the system of linked bodies is determined by the vector sum of the individual force components. The WAFAC model was incorporated into the Articulated Total Body (ATB) model to analyze the dynamics of the system of linked bodies subject to the water forces and moments. To validate the model, simple geometries such as spheres and ellipsoids were modeled and the results compared with analytical solutions.

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DEVELOPMENT OF A SOFTWARE TOOL TO ANALYZE PERSONAL FLOTATION DEVICES

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ABSTRACT A computer program, WAFAC (WAter Forces Analysis Capability), was developed to analyze forces acting on bodies in water. The WAFAC model computes buoyancy, wave-excitation, added-mass, and drag forces acting on a system of linked bodies in water. The bodies are assumed to be rigid ellipsoids. Sea states can be approximated by the superposition of up to ten regular waves or by a single regular wave of amplitude equal to the "significant wave height" and frequency based on the statistical parameters of the Pierson-Moskovitz spectrum for fully developed ocean waves.

The WAFAC model is structured to compute components of force and moment due to buoyancy, wave-excitation, added-mass, and drag using separate modules. During development, each module was tested to assess the accuracy of the results predicted. The resultant water force and moment acting on each ellipsoid in the system of linked bodies is determined by the vector sum of the individual force components.

The WAFAC model was incorporated into the Articulated Total Body (ATB) model to analyze the dynamics of the system of linked bodies subject to the water forces and moments. The ATB model, developed by the Air force, is a sophisticated human body dynamics computer program capable of analyzing 3-dimensional motion of linked segments subject to external forces and prescribed acceleration fields. Also, the model can handle a number of different types of joints to connect the segments. This model has been widely used in crash victim simulations. Its ability to simulate the behavior of a person in such situations is well documented[1].

In order to validate the WAFAC model, it was exercised to predict the forces on bodies with simple geometries such as spheres and ellipsoids and the results compared with analytical solutions. Further qualitative validations of the model were performed by using it to simulate the motion of humans wearing PFDs and exposed to a variety of water surface conditions. The humans in these simulation runs were represented by 50th percentile Hybrid III dummy data sets.

The output from the WAFAC model consists of two binary files containing data for plotting time histories of selected dynamic variables and data for showing the motion of the human in pictorial form. An ASCII file that can be printed out is also generated. A PC- and Silicon Graphics Workstation based post-processor was also developed to allow the user to examine the dynamics of the bodies in water and to plot the simulation results.

INTRODUCTION

With the rising number of drownings and near drownings reported in the US[2], evaluation of the performance of personal flotation devices (PFDs) has become a concern in both civilian and military applications. The United States Coast Guard (USCG), in particular, has been engaged in a long range scientific study to develop PFD performance standards which ensure adequate rough water flotation for the general population[3].

The performance of PFDs is currently evaluated by conducting immersion experiments using human volunteers. These experiments pose several problems, e.g., failure of the subject to remain passive and non-repeatability of results. Also, the

data from human immersion tests are sometimes difficult to interpret as they seem to depend on a number of diverse parameters. Studies have indicated the possible dependence of results even on the time of the day the experiments were performed[4]. Furthermore, quantitative data that can be related to the effectiveness of a PFD, such as freeboard and angle of repose, are difficult or impossible to measure.

Some of these problems involved with the use of human volunteers can be alleviated by the use of anthropometric dummies as subjects. The use of dummies is especially helpful in efforts towards standardizing tests and evaluation procedures. Even though dummies have been used in experiments for sometime, the development of a true sea worthy anthropometric dummy has been reported only recently[5]. Human or dummy immersion tests require careful planning of experimental protocols and data collection techniques. Also, proper execution of experiments require a considerable amount of time and resources.

Computer modeling can provide a means of addressing these difficulties. Data that cannot be measured in testing can be calculated and numerous parameter studies can be conducted for only the cost of computer time. Also, computer modeling can be a powerful tool in evaluating the performance of PFDs when used in conjunction with immersion experiments. All mathematical models are based on assumptions. Therefore, before using any model, it should be properly validated. The results of a few carefully planned and executed immersion experiments using dummies or human volunteers can be used in the validation process. The validated model can then be used to simulate the motion of a person in water for any number of conditions that comply with the assumptions the model is based on.

The objective of the current study was to introduce a water forces analysis capability to the Articulated Total Body (ATB) model, developed by the Air Force, so that it can be used to evaluate performance of PFDs. The ATB model is a sophisticated human body dynamics computer program capable of analyzing 3-dimensional motion of linked segments subject to external forces and prescribed acceleration fields. Also, the model can handle a number of different types of joints to connect the segments. This model has been widely used in crash victim simulations. Its ability to simulate the behavior of a person in such situations is well documented[1].

METHODOLOGY

In this study, we developed a model that includes the most important features needed to analyze the performance of PFDs and one that can easily be enhanced to include more advanced features.

The WAFAC model treats the ellipsoids associated with a system of linked segments as a set of discrete ellipsoids when computing water forces acting on the whole system; i.e., the water force acting on each ellipsoid is evaluated separately without allowing for either the blocking effects of closely located ellipsoids or the effects of overlapping ellipsoids. The model also disregards the effects of neighboring ellipsoids on the local flow pattern around a given ellipsoid.

WATER FORCE COMPONENTS MODELLED BY WAFAC

Each point on the wetted surface of

a body in water experiences a pressure due to hydrostatic, wave-excitation, added-mass, drag, and wave-scatter effects. As the potential use of the model will be to analyze situations where the person in water does not significantly affect the incident waves by causing wave-scatter, all but the last pressure effect mentioned above are computed by the WAFAC model.

The total water force acting on the body is the integral of the pressure over the wetted surface. This water force may impart a torque on the body equal to the integral of the moment of the pressure over the wetted surface. WAFAC is structured to model each force component due to hydrostatic, wave-excitation, added mass, and drag forces separately. Presented below are the details of each force component calculation as performed by the WAFAC model.

BUOYANCY EFFECTS

The hydrostatic or the buoyancy pressure at a point is equal to the product of the specific weight of water and the vertical distance to the point from the free-water surface.

WAVE EXCITATION EFFECTS

The presence of incident waves give rise to wave excitation forces and moments acting on the body. In the WAFAC model, the free-water surface is described using linear theory. Two boundary conditions, one kinematic and one dynamic, define the free-water surface. The kinematic boundary condition requires that the normal velocities of the fluid and the free-water surface be equal. The dynamic boundary condition requires the pressure on the free surface to be atmospheric.

Figure 1. depicts the various parameters used to define the free-water surface. In this figure, the Mean Water Surface (MWS) is defined by the X-Y plane of the "water frame" which is placed with its Z-axis pointing vertically down. In the WAFAC model, the user can define the origin and the orientation of this "water frame". The vertical elevation of a point on the free-water surface is denoted η.

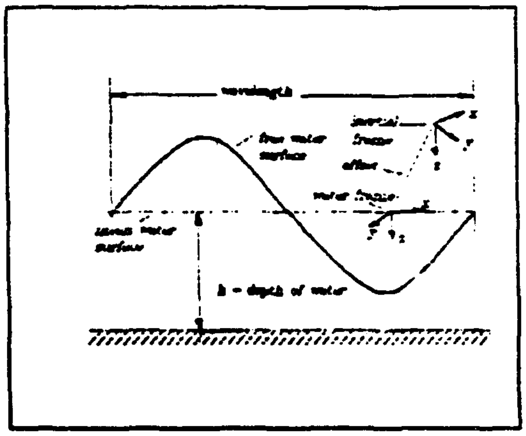

Figure 1. Water frame and the parameters defining the free-water surface wave.

The viscous and surface tension effects at the free-water surface are neglected. As a result, the fluid velocity, v, is expressed by the gradient of a velocity potential function, ϕ. Also, the slopes of the wave surface in the X and Y directions of the water frame are assumed small compared with unity, and the gradients of the velocity potential in the X and Y directions are assumed to be small first order quantities. The resulting linearized kinematic condition is combined with a dynamic boundary condition obtained by applying Bernoulli's equation and neglecting the second order quantity in the fluid velocity.

The simplest solution for the resulting free-water surface

condition yields a system of regular (or plane progressive) waves. These are two-dimensional, sinusoidal waves with a frequency of ω. The general form of the free-surface elevation, η, due to a regular wave progressing at an angle β with the positive x-axis and a phase difference of ϵ is given by:

$$\eta(x,y,t) = A \cos\theta \qquad (1)$$

where A is the wave amplitude, k is the wave number, ω is the frequency and θ is given by:

$$\theta = k(x \cos\beta + y \sin\beta) - \omega t + \epsilon \qquad (2)$$

In terms of the wavelength λ, k is defined as:

$$k = 2\pi/\lambda \qquad (3)$$

In the WAFAC model, the water depth can be input as a finite depth, h, with an impermeable bottom or as very large (infinite). For finite depth, h, the solution for velocity potential is:

$$\phi = \frac{gA}{\omega}\frac{\cosh k(h-z)}{\cosh kh} \sin\theta \qquad (4)$$

where,

$$k \tanh kh = \omega^2/g \qquad (5)$$

For large depths, $h \to \infty$ and $\cosh k(h-z)/\cosh(kh) \to e^{-kz}$. Then, the velocity potential reduces to:

$$\phi = \frac{gA}{\omega} e^{-kz} \sin\theta \qquad (6)$$

$$k = \omega^2/g \qquad (7)$$

As a rule of thumb the large depth approximations can be applied when h > one-half the wavelength λ.

In the linearized theory, solutions may be superimposed without violating the boundary conditions or the governing Laplace's equation. The WAFAC model allows the user to utilize up to ten regular waves to describe the free-water surface. The program will superimpose the components due to each wave in computing the free-water surface height η and the velocity potential ϕ.

The WAFAC model also allows the user to represent sea states by a single regular wave based on the statistical parameters of the Pierson-Moskovitz spectrum[5] for fully developed ocean waves. The semi-empirical expression for the frequency spectrum of fully developed waves is:

$$S(\omega) = \frac{0.0081g^2}{\omega^5} e^{-0.74\left(\frac{g}{U\omega}\right)^4} \qquad (8)$$

where U is the wind velocity, in knots, at a standard height of 63.98 ft (19.5 m) above the free surface, and g is the acceleration of gravity (386.1 in^2/s). The height of the wave representing ocean conditions is taken to be the "significant wave height", $H_{1/3}$, defined as the average of the highest one third of all the waves. $H_{1/3}$ is given by:

$$H_{1/3} = 0.209246 \frac{U^2}{g} \qquad (9)$$

The average frequency ω of the spectrum is given by:

$$\omega = (0.74\pi)^{1/4}(g/U) \qquad (10)$$

user inputs the value of U. The wavelength is calculated assuming infinite depth.

The wave-excitation pressure due to incident waves is equal to the product of the time derivative of the potential function describing the water surface and the mass density of water. When a number of regular waves are used to describe the water surface, the total wave excitation pressure is computed as the sum of pressures due to each regular wave. The velocity potential decays with increasing depth z, and the wave excitation

effects decrease with increasing depths. Generally, the wave excitation forces are confined to a water layer of thickness approximately equal to one-half the wave length[6]. However, the WAFAC model evaluates the forces and moments due to wave excitation effects irrespective of the depth of submergence of the object.

The buoyancy and wave-excitation forces and moments are evaluated using a numerical scheme based on the Simpson's method. This scheme assumes the body to be ellipsoidal. As shown in Fig. 2, a two-dimensional grid is generated on the ellipsoid surface by using the distance along the first semi axis for the ellipsoid, "X", as one coordinate and the azimuthal angle ϕ generated on a plane perpendicular to this axis as the second coordinate. The user can control the size of the mesh by changing input parameters. For each elemental grid area, it is determined whether the center of the element is "in" or "out" of the water. When the center is "in" the water, the whole grid element is considered to be under water and vice-versa. When under water, the pressure due to buoyancy and wave excitation forces at the center of the grid element is multiplied by the area of the grid element. These forces are vectorially added using a numerical integration scheme based on the Simpson's method.

ADDED-MASS EFFECTS

When a body accelerates through water, a volume of fluid accelerates with it. Added-mass effects are a weighted integration of the inertia of this entire mass. Since the bodies modelled with the WAFAC model are not expected to acquire high angular accelerations and velocities, the WAFAC model computes only the translational added mass

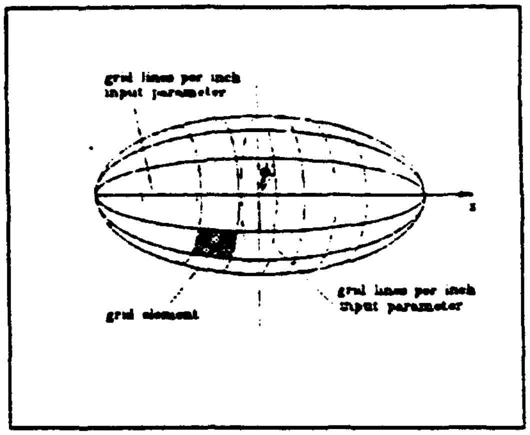

Figure 2. Illustration of the grid used to evaluate buoyancy and wave-excitation forces and moments.

effects. These effects are modelled by increasing the mass of the body by an amount equal to the product of the mass of the volume of water displaced by the body and an added-mass coefficient defined by the user. The model assumes a single added-mass coefficient in all three translational degrees of freedoms (surge, sway and heave) for a given ellipsoid.

DRAG EFFECTS

The three pressure effects discussed above do not account for frictional (mainly pressure drag) effects. However, one potential application of the model is to study the motion of a person (with or without a PFD) dropped into the water from a height above the free-water surface. The ensuing motion will be affected to a significant extent by the pressure drag exerted by the water. Without this drag the person will undergo indefinite periodic motion. The total drag force is modelled as two components, one along but opposite to the direction of motion, F_D, and the other, F_L, normal to it.

F_D is computed as:

$$F_D = \frac{1}{2} C_D A_{proj} \rho V^2_{rel} \tag{11}$$

This drag force component acts in the direction of V_{rel} which is the difference between the velocity of water, and the velocity of the body, at the location of the centroid of the displaced volume of water. The coefficient C_D is a user defined drag force coefficient for the body and ρ is the density of the water. A_{proj} is found by projecting the displaced volume on to a plane normal to the relative velocity V_{rel}.

F_L is computed as:

$$F_L = \frac{1}{2} C_L \sin 2\alpha \, A_{proj} \, \rho V^2_{rel} \tag{12}$$

where α is the angle between vectors V_{rel} and n. The vector n is the normal to the plane defined by all the points on the body that are tangential to V_{rel}. This lift force is assumed to vary as a Sine function and the body is assumed to be ellipsoidal. It acts perpendicular to V_{rel} and attains a maximum value when α is 45 degrees.

The form adopted in Eqs. 10 and 11 for drag and lift forces with constant coefficients C_D and C_L are suitable for flows where the skin drag (due to viscous effects) is significantly lower than the form drag (due to pressure differentials). For spheres and ellipsoids in unbounded flows, the drag coefficient is roughly constant for a Reynolds number ($\Re$) range of approximately $10^3 < \Re < 10^5$ ($\Re$ = Va/ν, ν= kinematic viscosity, and "a" is a characteristic length). For $\Re < 10^3$, C_D is a function of $\Re$. However, at these low Reynolds numbers the velocity has to be very small as the kinematic viscosity of water is around 2.0×10^{-5} ft^2/s. Under these circumstances, the magnitude of the viscous drag becomes negligibly small as it is proportional to the velocity squared. This being the case, to find viscous drag on ellipsoids in water, the form adopted in Eq. 10 is adequate.

OUTPUT OF THE MODEL

The WAFAC model produces two types of output, in addition to the output data produced by the ATB model, which includes body segment linear and angular positions, velocities, and accelerations, and joint orientations, forces, and torques. The standard WAFAC output consists of the time histories of the ratio of body in water to total body volume (the sum volume of all ellipsoids allowed to contact water is taken as the total body volume), the distance between the mouth and the water surface, the area of water surface broken by the body, the net body kinetic energy, and the azimuth and elevation angles of body repose.

The optional output can be generated for several sequences of ellipsoids. A sequence of ellipsoids may consist of one or more of the ellipsoids that can contact water. This option can create any of the following time histories for a given sequence of ellipsoids: The total water force and torque, buoyancy force and torque, wave-excitation force and torque, added-mass force, and drag force. The user can define the coordinate system in which the output is to be generated.

Two utility programs were developed to aid in viewing the output from the WAFAC model on a Silicon Graphics platform. One is a solid model display routine for depicting the body motion and the other is a plotting routine for graphing time history output. Also the wire-frame type graphics program, VIEW, used with the ATB model, was enhanced to

display the water surface.

RESULTS AND VALIDATIONS

Preliminary validations of the WAFAC model were carried out using simple geometries such as spheres and ellipsoids. Whenever possible, the results were compared with analytical solutions. Then, a qualitative analysis of the motion of humans wearing PFDs was performed using a 50th percentile Hybrid III dummy data set and a variety of water surface conditions.

To test the robustness of the model in buoyancy force calculations, a number of simulations were run where small vertical perturbations were given to ellipsoids of different shapes and sizes floating half submerged in still water. It can be shown that the heave period of oscillations for an ellipsoid floating half submerged in still water is $2\pi(2c/3g)^{0.5}$, where g is the acceleration of gravity and c is the semi axis of the ellipsoid oriented vertically. Spheres, spheroids, elongated ellipsoids that were flat, elongated ellipsoids that were thin and long in the vertical direction etc., were simulated. The predicted periods of small vertical oscillations were within 0.2% of the theoretical values.

To test the prediction of buoyancy forces for pitching ellipsoids, we ran a number of simulations with ellipsoids where the period of oscillations for small angular perturbations about the equilibrium position were obtained. The theoretical value for the period is $8\pi[c(c^2+a^2)/15ga^2]^{0.5}$, where "a" is the length of the semi axis about which the ellipsoid is given the angular displacement. Our results were within 1%. It should be noted that the theoretical value is based on simplifying assumptions that linearize the situation modelled.

As wave-excitation forces are computed numerically using a grid, we conducted a detailed study to examine variation of model results with grid size. A number of ellipsoids of different sizes and shapes were positioned in different parts of waves of different amplitudes and wavelengths and the grid size changed till the model results did not change appreciably. The results show that a grid with 15 divisions along the "X" axis and 20 divisions in the azimuthal direction will be adequate for ellipsoids of size equal to those defining the torso of the Hybrid III dummy.

Qualitative analysis of the WAFAC model was done using a 50th percentile Hybrid III male dummy as a subject in water. A Soniform life jacket was modelled by 5 PFD ellipsoids. A Hybrid III dummy wearing this PFD is illustrated in Fig. 3. The Hybrid III weighs 167.98 lb. and has a buoyancy of 141.33 lb. The five PFD ellipsoids has a total volume of 965 in^3 with a buoyancy of 35 lb. This gives the Hybrid III a net buoyant weight of 8 lb. In the first simulation, the Hybrid III dummy with the PFD was placed in static water and a small vertical perturbation was given. The simulation showed a periodic motion as anticipated. Next, a drag coefficient of 0.3 was defined for all the ellipsoids defining the Hybrid III dummy and the test repeated. The amplitude of the periodic oscillations decreased with time as anticipated. In the third simulation the Hybrid III dummy with the PFD was dropped on to the crest of a wave of amplitude 12" and wavelength 300" from a height of 50 in. The simulation results showed that the dummy surfaced in 4 sec. rode with the wave or close to the wave surface for the rest of the duration of the simulation (which was 8 sec). Fig. 4 shows the water surface and the position of the

dummy at several different stages of this simulation. Two more simulations were run to examine the robustness of the software by changing the water surface conditions. In both simulations, the dummy was initially placed at a wave crest. In the first, the surface was described by a standing wave defined by two identical waves travelling in opposite directions. In the second, the water surface was defined by two identical waves travelling normal to each other. The simulations were run for more than 10 sec. In both simulations the dummy remained close to the surface. The motion of the dummy seemed to be realistic.

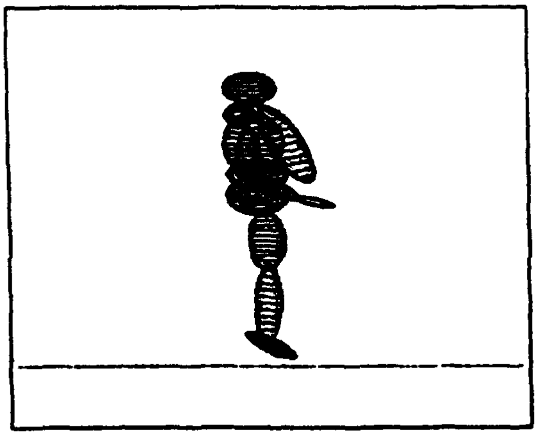

Figure 3. Hybrid III dummy wearing a Soniform PFD represented by five ellipsoids.

Future validation of the WAFAC model is planned by the U.S. Coast Guard and the Armstrong Laboratory. Results from controlled tests will be compared with simulation results. The tests will start with simple geometric shapes in calm water and waves, and eventually include whole bodies with PFDs.

RECOMMENDATIONS FOR FUTURE ENHANCEMENTS

In addition to further validation, recommendations for future work in this area include some enhancements that will improve the capabilities and the efficiency of the current version of the WAFAC model.

The variation of added mass effects due to different coefficients in heave, sway and surge should be considered. In order to accomplish this, the governing (system) equations of the ATB model will have to be modified allowing for the three components of translational added mass coefficients.

The WAFAC model considers each ellipsoid in a system of linked segments separately when determining water forces. Thus, when the ellipsoids are overlapping, the WAFAC model may overestimate the water forces acting on the system of linked segments. A scheme for each force component should be developed to methodically compensate for the effects of overlapping ellipsoids. In the case of drag and added mass effects, one possible approach is to include an option to represent several ellipsoids by an equivalent ellipsoid.

Representation of the free-water surface could be improved by employing non-linear theory. Much of the second order theory has been worked out and can be found in a number of texts[6]. The main task would be to develop the computer algorithms for calculating these effects.

SUMMARY AND CONCLUSIONS

We have developed a software tool to analyze performance of Personal Flotation Devices under a variety of water surface conditions. The water forces as predicted by the model that act on bodies with simple shapes such as spheres and ellipsoids compare well with analytical solutions. Qualitative results with Hybrid III dummies

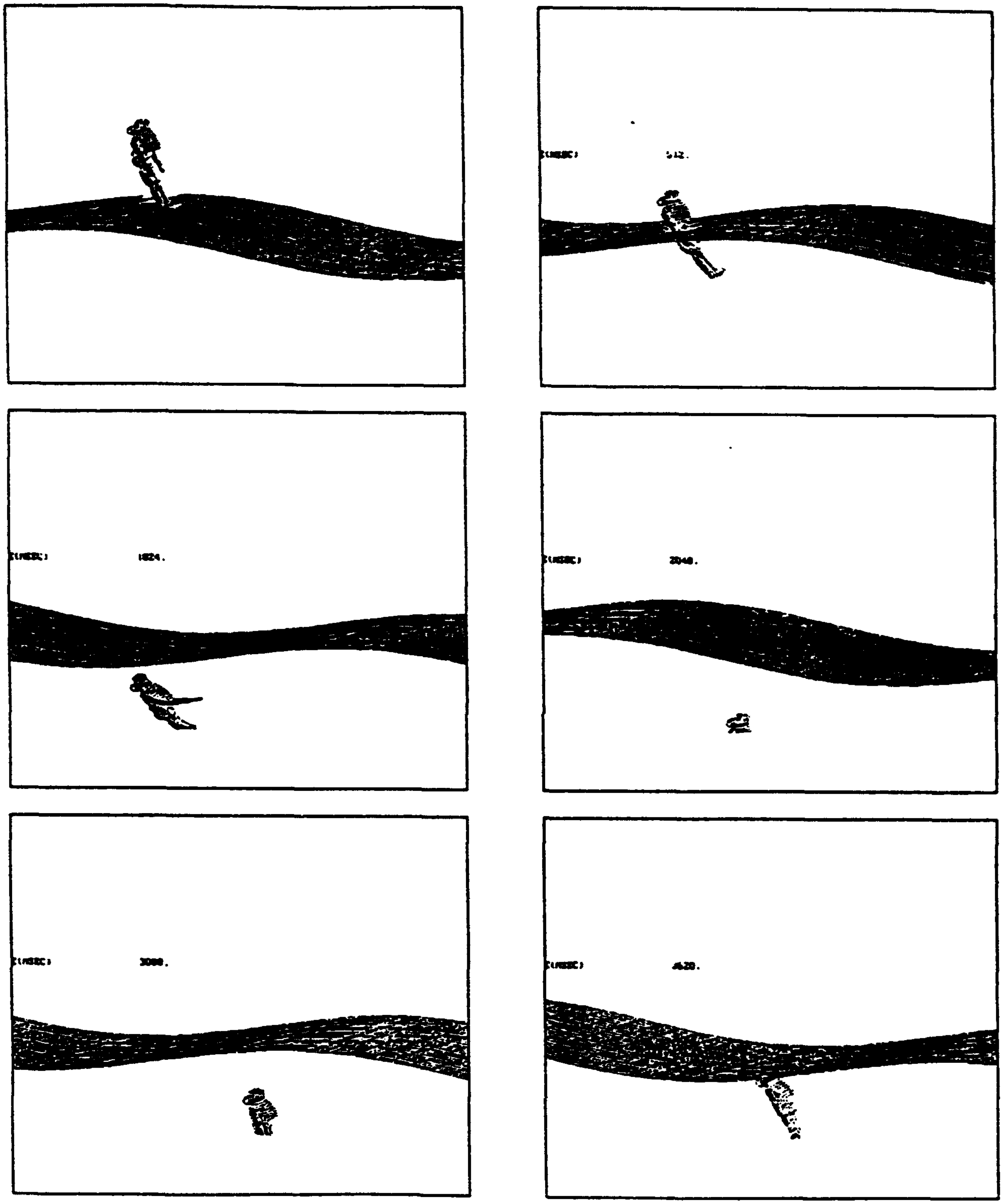

Figure 4. The motion of a Hybrid III dummy wearing a Soniform PFD approximated by 5 ellipsoids. The dummy is dropped from a height of 50 in. (measured to the lower torso) onto the crest of a wave. The frames show the position of the wave and the dummy at 0, 512, 1024, 2048, 3008, and 3520 msec.

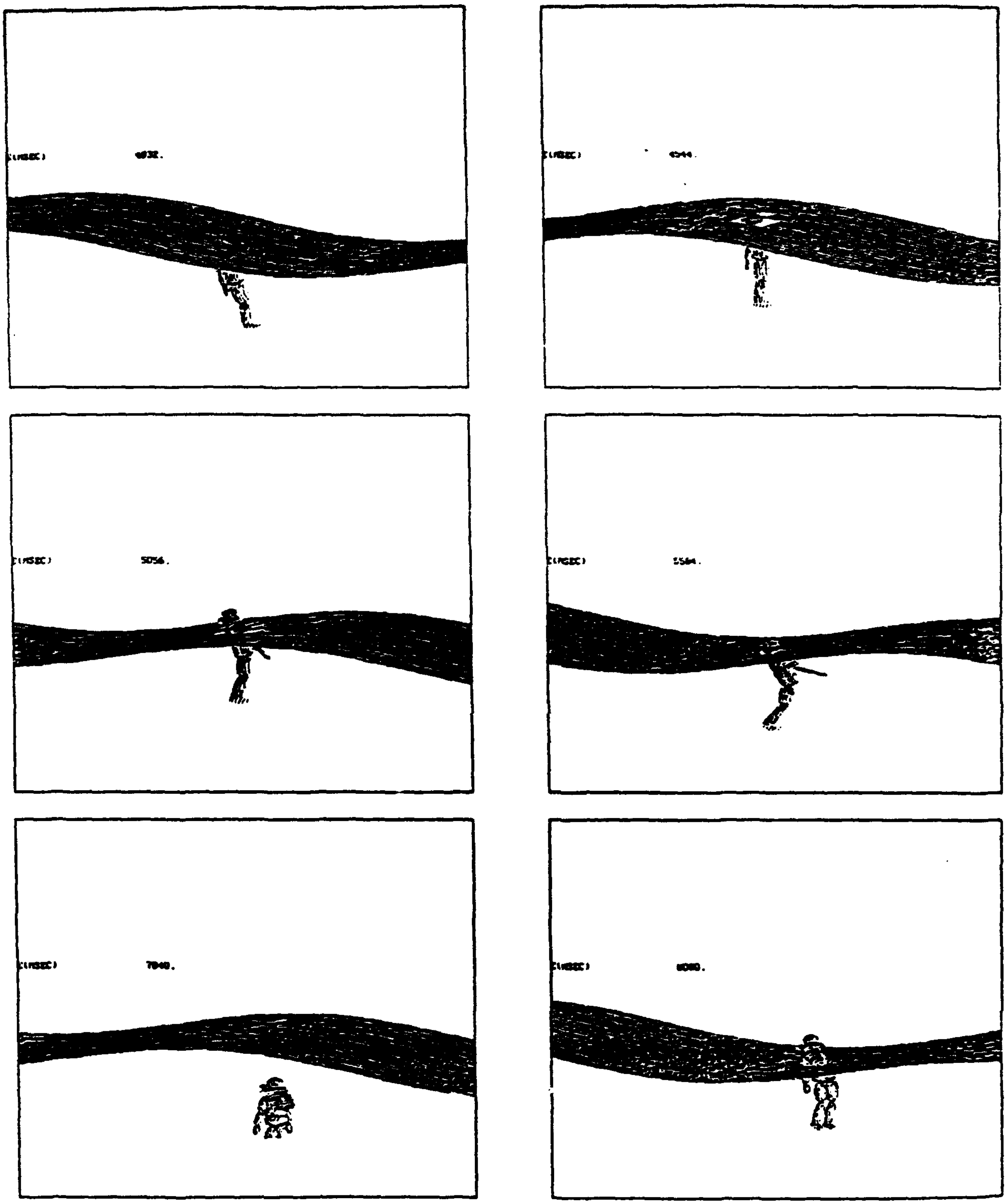

Figure 4 (cont.) The frames show the position of the wave and the dummy at 4032, 4544, 5056, 5504, 7704, and 8000 msec.

wearing PFDs are realistic. Future comparison with actual test results are recommended for further validation.

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